Kinematic Coupling for Precision Fixturing & Assembly

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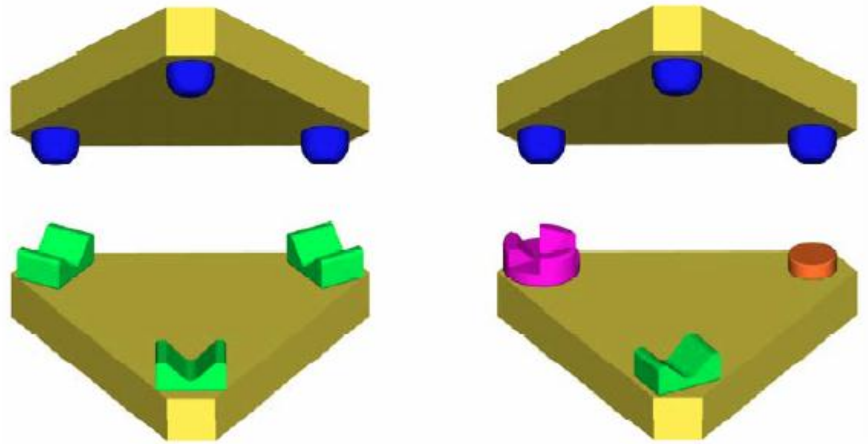
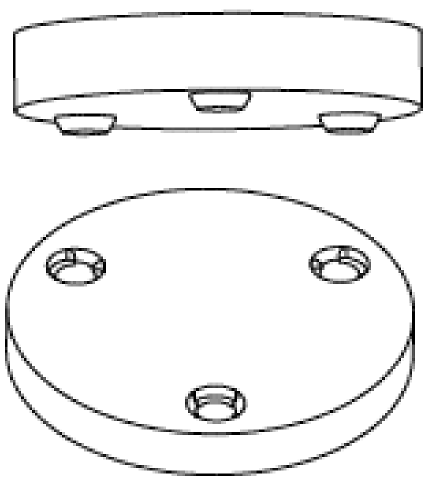
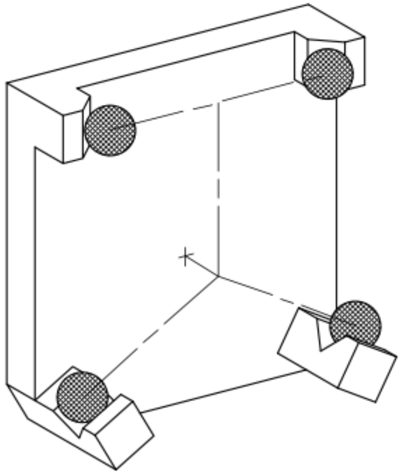
material from
Profs. Alexander H. Slocum & Martin Culpepper
http://pergatory.mit.edu/
http://www.kinematiccouplings.org/

OUTLINE

- Kinematic Coupling Overview
- Hertz Contact Review
- Types
  - Standard
  - Canoe (High Load)
  - Compliant
  - Three Tooth
- Case Studies
  - Servo Controlled
  - Ford (Duratec™) QKC
- Elastic Averaging

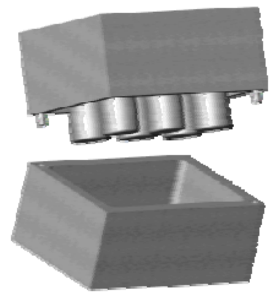




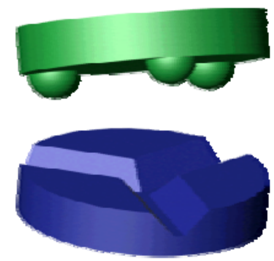


Review of Coupling Methods

Elastic Averaging
Non-Deterministic



Pinned Joints
No Unique Position



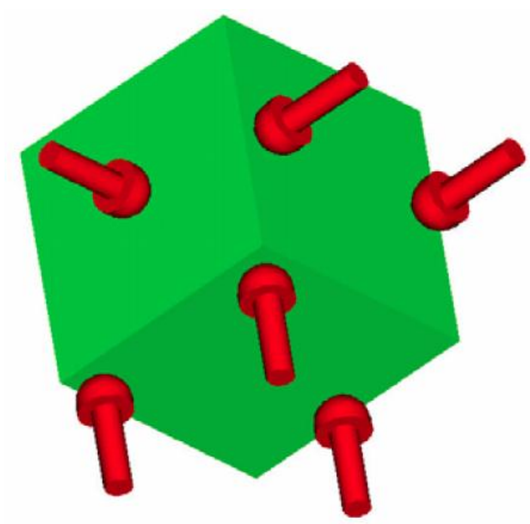
Kinematic Couplings
Kinematic Constraint

Flexural Kin. Couplings
Kinematic Constraint

	0.01 µm	0.1 µm	1 µm	10 µm	100 µm
Pinned Joints					
Flexural Kinematic Couplings					
Elastic Averaging					
Quasi-Kinematic Coupling					
Kinematic Couplings					

Kinematic Coupling Overview

- When a component is constrained by a number of points equal to the number of degrees of freedom, it is said to be exactly constrained.
  - # Points of Contact = # Degrees of Freedom Constrained
  - 3 Axial & 3 Rotation
- Low-Medium Force Precision Applications
- Do Not Allow Sealing Contact
- Moderate Stiffness
- Moderate Cost
- Excellent repeatability
  - 1/4 micron common
  - On order of surface Finish



Hertz Contact Interface

- Equivalent Modulus

$$E_{eqivalent} = \frac{1}{\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}}$$

- Equivalent Radius

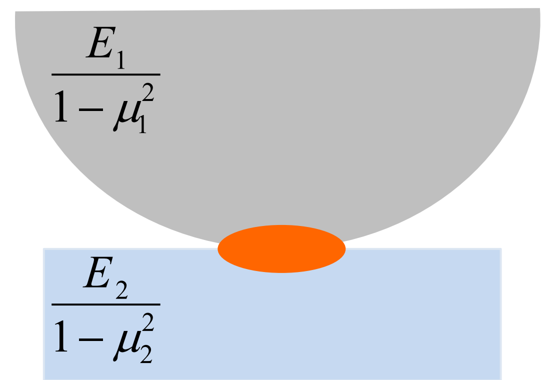
$$R_{eqivalent} = \frac{1}{\frac{1}{R_{1,mjr}} + \frac{1}{R_{1,mnr}} + \frac{1}{R_{2,mjr}} + \frac{1}{R_{2,mnr}}}$$

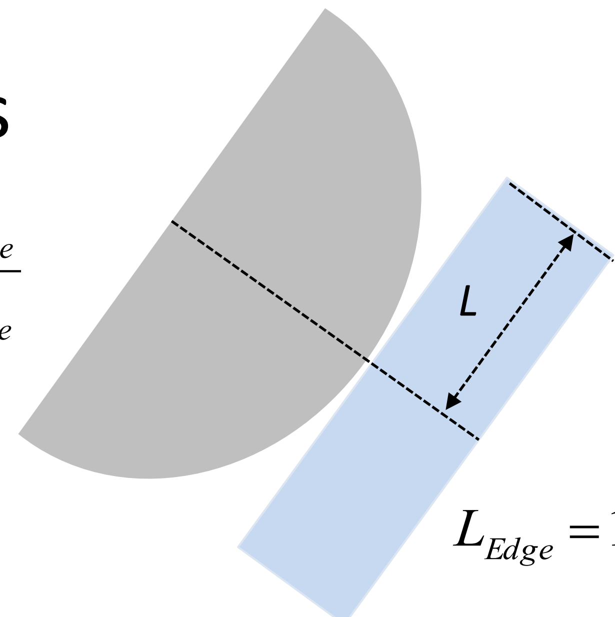
- Contact Radius and Stress

$$a_{contact} = \left(\frac{3 \cdot F \cdot R_e}{2 \cdot E_e} \right)^{1/3} \qquad q_{contact} = \frac{a \cdot E_e}{\pi \cdot R_e}$$

$$q_{HertzMax} = \frac{2 \cdot \sigma_{allowable}}{1 - 2 \cdot \mu}$$

* Keep Contact Stress Below Elastic Limit



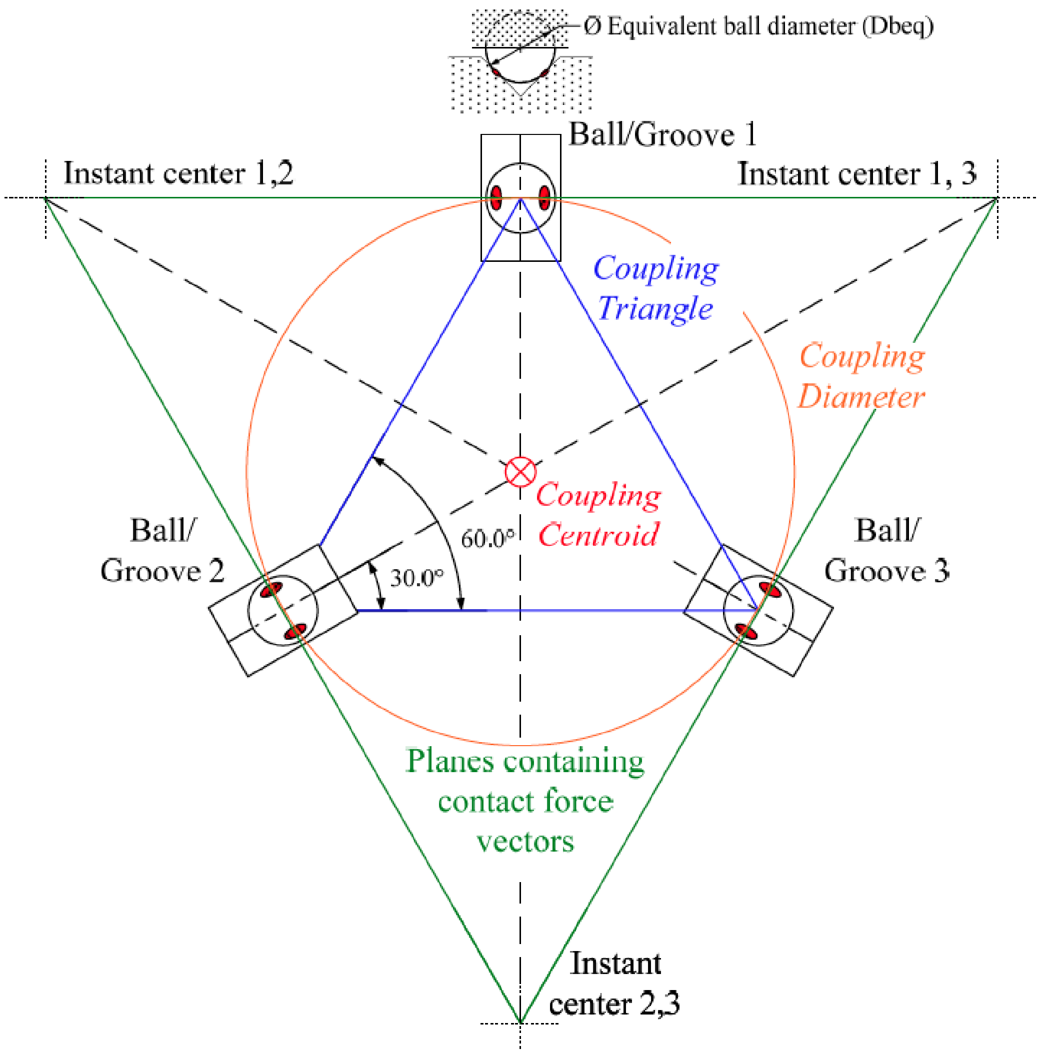


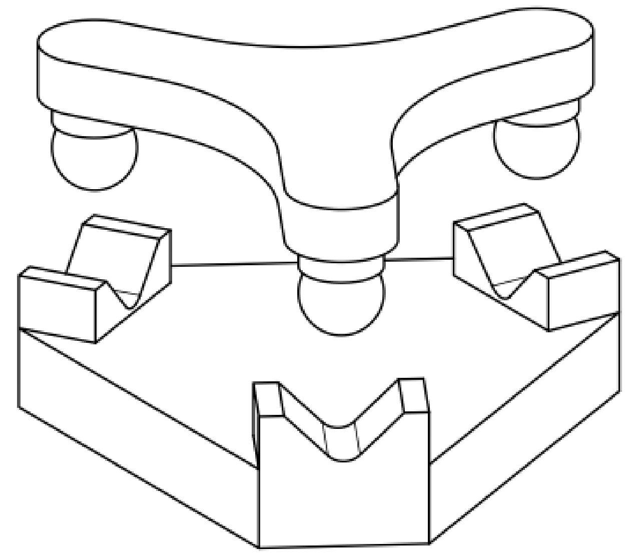
$$L_{Edge} = 10 \cdot a_{contact}$$

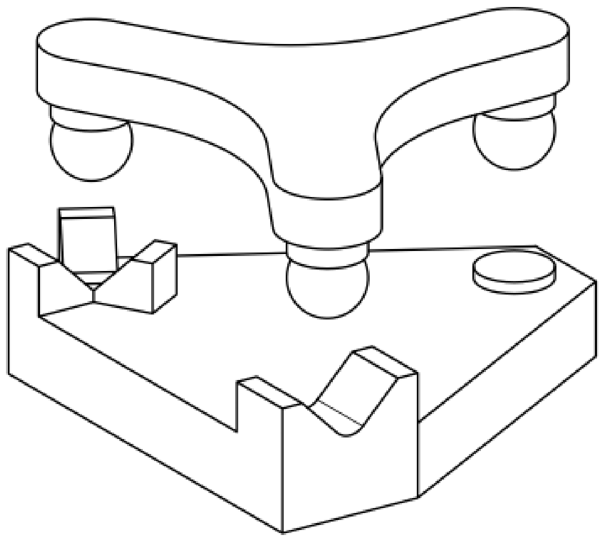
Key Hertz Relations

- Contact Pressure is proportional to:
  - Force to the 1/3rd power
  - Radius to the –2/3rd power
  - Modulus to the 2/3rd power
- Deflection is proportional to:
  - Force to the 2/3rd power
  - Radius to the –1/3rd power
  - Modulus to the –2/3rd power
- Contact ellipse diameter is proportional to:
  - Force to the 1/3rd power
  - Radius to the 1/3rd power
  - Modulus to the –1/3rd power
- CAREFUL TO NOT ALLOW THE CONTACT ELLIPSE TO BE WITHIN ONE DIAMETER OF THE EDGE OF A SURFACE!

Standard KC

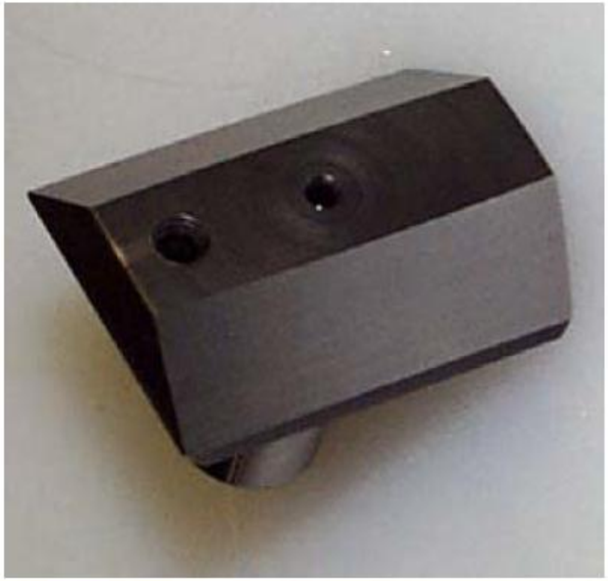

Ø Equivalent ball diameter (Dbeq)
Ball/Groove 1
Instant center 1,2
Instant center 1, 3
Coupling Triangle
Coupling Diameter
Coupling Centroid
60.0°
30.0°
Ball/ Groove 2
Ball/ Groove 3
Planes containing contact force vectors
Instant center 2,3

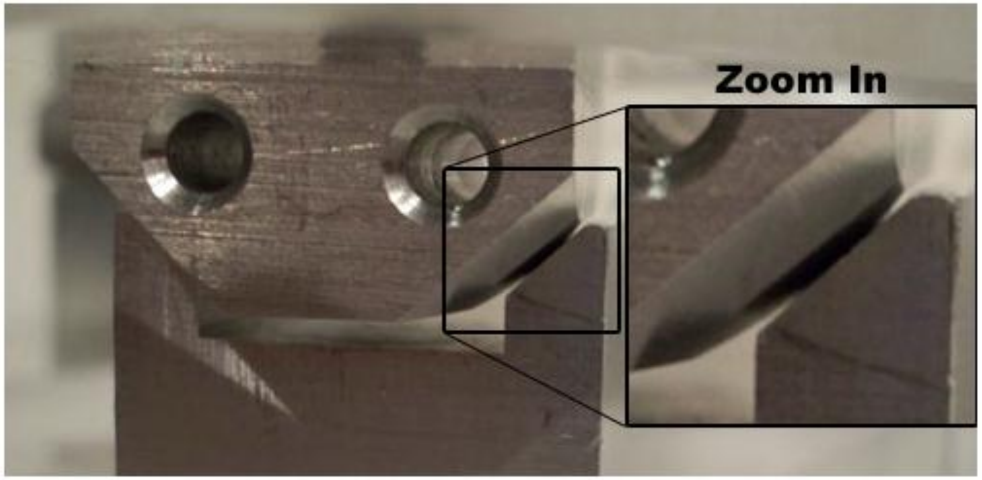




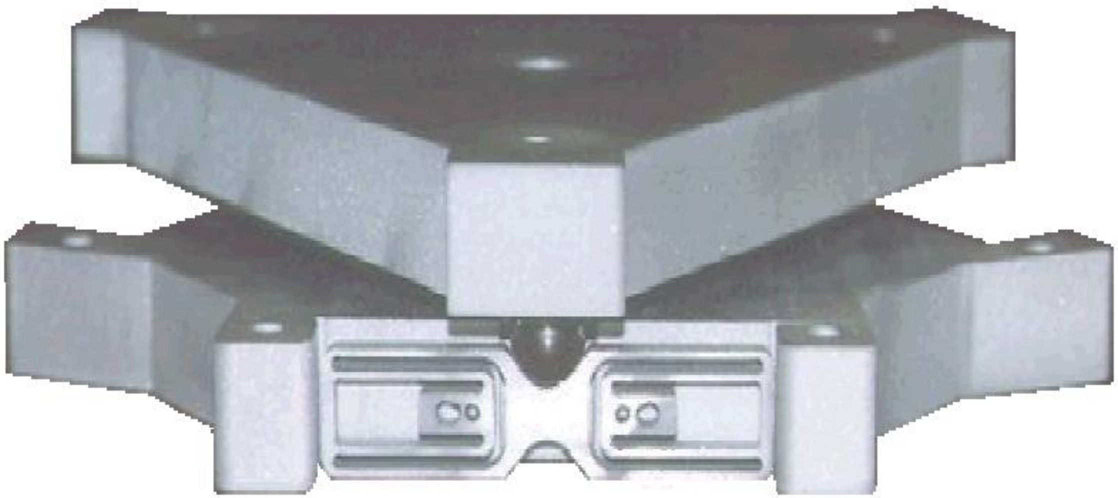
Canoe-Ball Kinematic Interface for High Load Applications

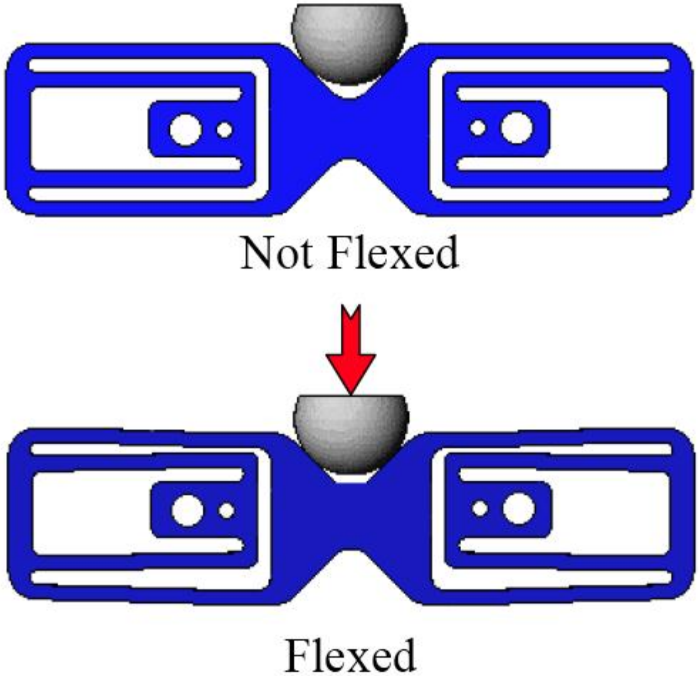
- The "Canoe Ball" shape acts like a 1m diam ball
- 100 times the stiffness & load of normal 1" ball
- 10 times load capacity of crowned cone
- Large Shallow Hertzian zone (very repeatable)
- US Patent 5,711,647





Compliant Kinematic Couplings



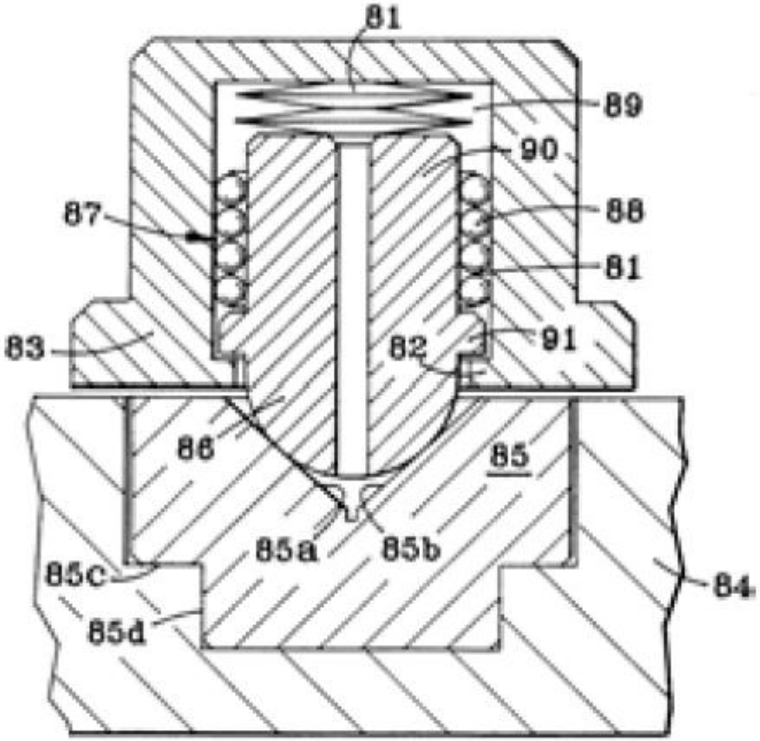


- Clamping Load/Friction/Mated Surface
- Joint Location
- Compliant Members
- Kinematic Interface

Compliant Kinematic Couplings

- Characteristics
  - Low Cost
  - Small – Medium Stroke
  - Precision 5 – 10 um
- Applications/Process
  - Assembly Lines
  - Stamping, Forging, Forming Equipment Die Alignment
  - Semiconductor Manufacturing Equipment
  - Casting Dies
- Cost
  - $10 – 200

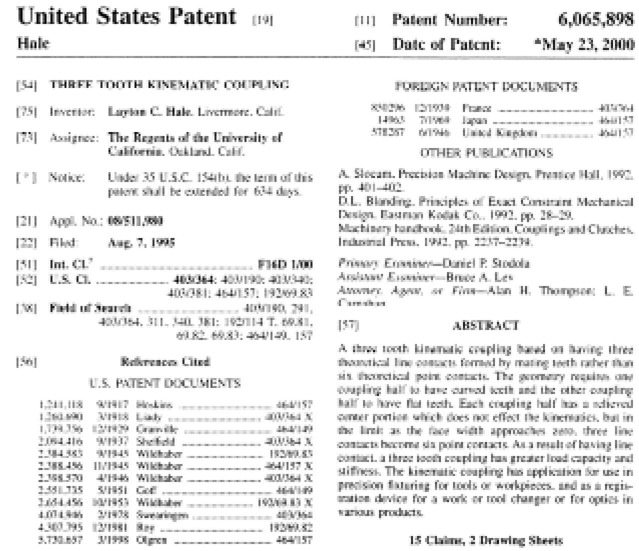
Compliant Kinematic Couplings



- Characteristics
  - Medium Cost
  - Long Stroke
  - Precision 2.5 um
- Applications/Process
  - Assembly Lines
  - Casting
  - Fixtures
- Cost
  - $2000

Three Tooth

- Semi-kinematic
- 6 point mating
- 3-5 micron repeatability
- Layton Hale (LLNL) added crowns to 1 set teeth yielding 1 micron repeatability



United States Patent [19]
Hale

[11] **Patent Number: 6,065,898**
[45] **Date of Patent: *May 23, 2000**

[54] THREE TOOTH KINEMATIC COUPLING

[75] Inventor: **Layton C. Hale**, Livermore, Calif.

[73] Assignee: **The Regents of the University of California**, Oakland, Calif.

[*] Notice: Under 35 U.S.C. 154(b), the term of this patent shall be extended for 634 days.

[21] Appl. No.: **08/511,980**

[22] Filed: **Aug. 7, 1995**

[51] **Int. Cl.**[7] **F16D 1/00**
[52] **U.S. Cl.** **403/364**; 403/190; 403/340; 403/381; 464/157; 192/69.83
[58] **Field of Search** .... 403/190, 291, 403/364, 311, 340, 381; 192/114 T, 69.81, 69.82, 69.83; 464/149, 157

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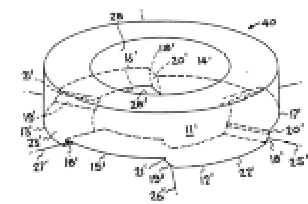
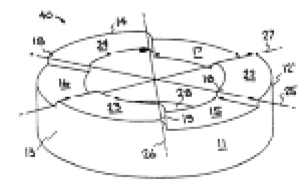
Primary Examiner—Daniel P. Stodola
Assistant Examiner—Bruce A. Lev
Attorney, Agent, or Firm—Alan H. Thompson; L. E. Carnahan

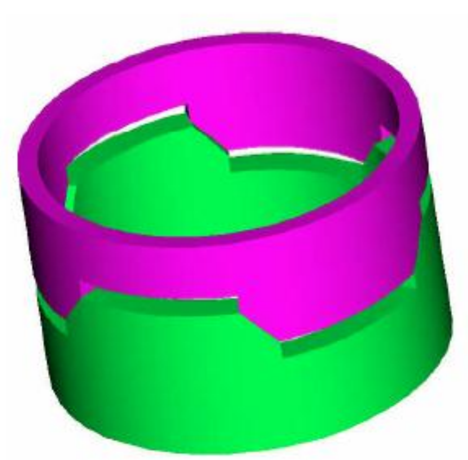
[57] **ABSTRACT**

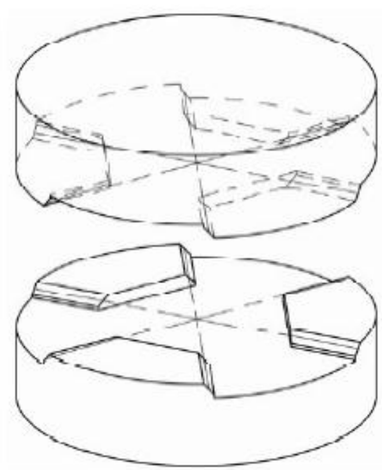
A three tooth kinematic coupling based on having three theoretical line contacts formed by mating teeth rather than six theoretical point contacts. The geometry requires one coupling half to have curved teeth and the other coupling half to have flat teeth. Each coupling half has a relieved center portion which does not effect the kinematics, but in the limit as the face width approaches zero, three line contacts become six point contacts. As a result of having line contact, a three tooth coupling has greater load capacity and stiffness. The kinematic coupling has application for use in precision fixturing for tools or workpieces, and as a registration device for a work or tool changer or for optics in various products.

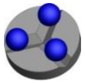
15 Claims, 2 Drawing Sheets





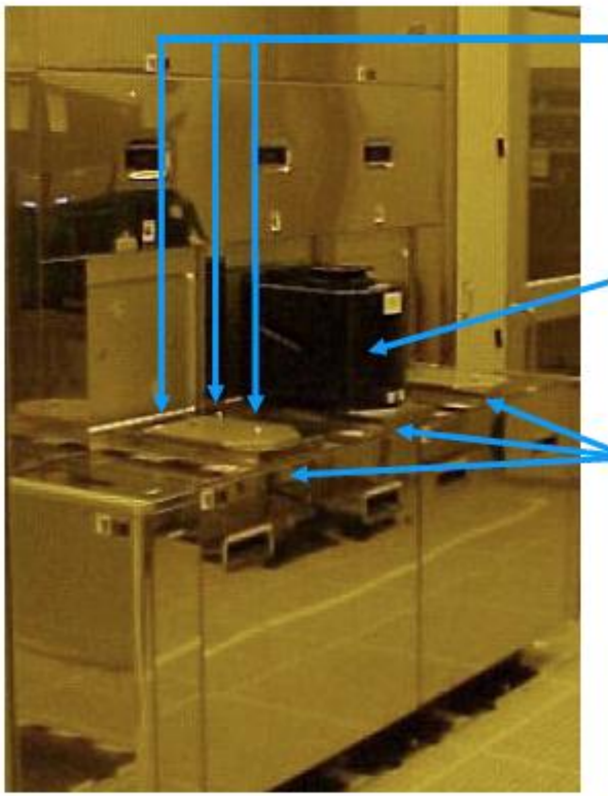






Wafer Transport

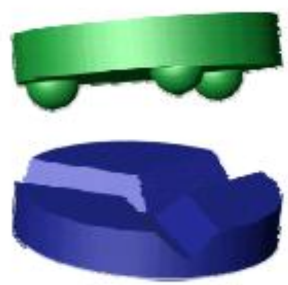
- How to precisely locate a plastic wafer carrying structure (FOUP) on a tool, so a robot can precisely load/unload wafers?
  - Exactly constrain it of course with an interface that contacts the FOUP at 6 unique points!
  - Success requires management of contact stresses, and standards upon which manufacturers agree
  - SEMI E57-1296 kinematic coupling standard for wafer transport pods



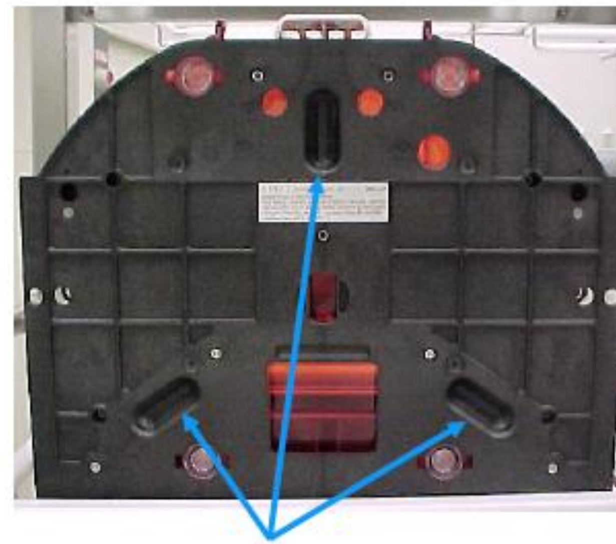
Kinematic coupling pins on loadport based on SEMI E57 standard

300mm Wafer carrier (FOUP) precisely positioned on kinematic coupling pins on loadport

Production equipment loadports based on SEMI E15.1 standard



Base of the FOUP



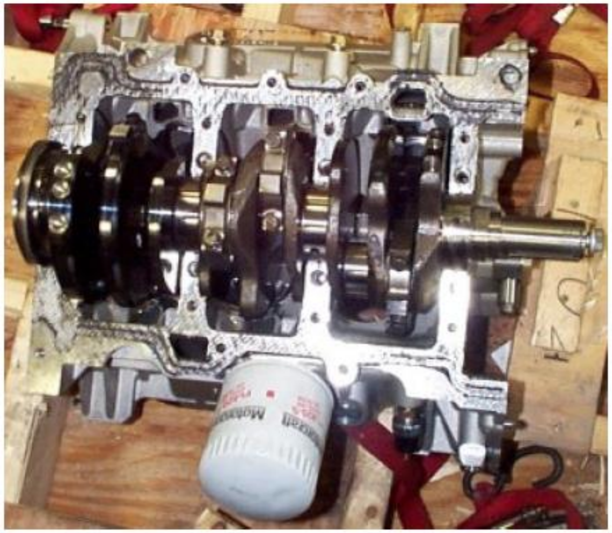
Mating kinematic coupling grooves on the FOUP, permitting precise alignment on load ports, so robots can precisely access 300 mm wafers

Ford 2.3 L V-6 Duratec™

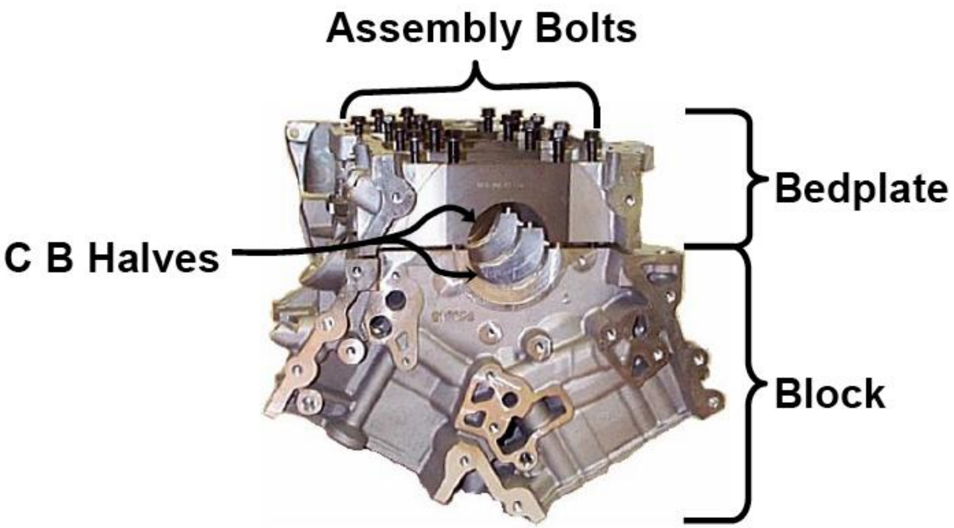
COMPONENTS

Block

Bedplate

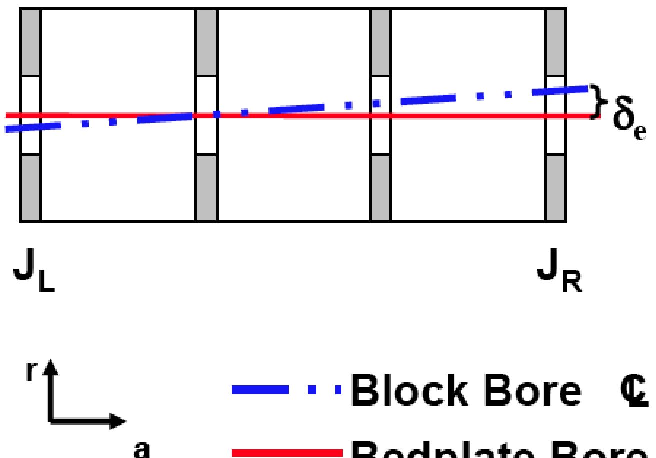


ASSEMBLY

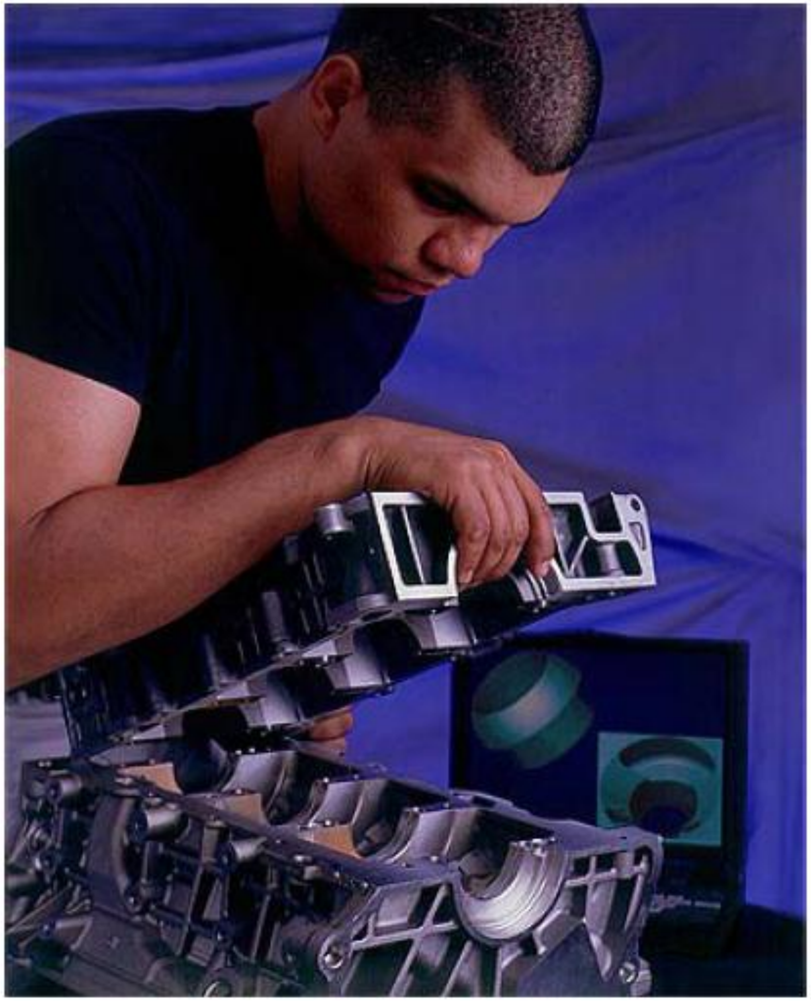


ERROR

δ_e MAX = 5 microns



Quasi Kinematic Couplings (QKCs)

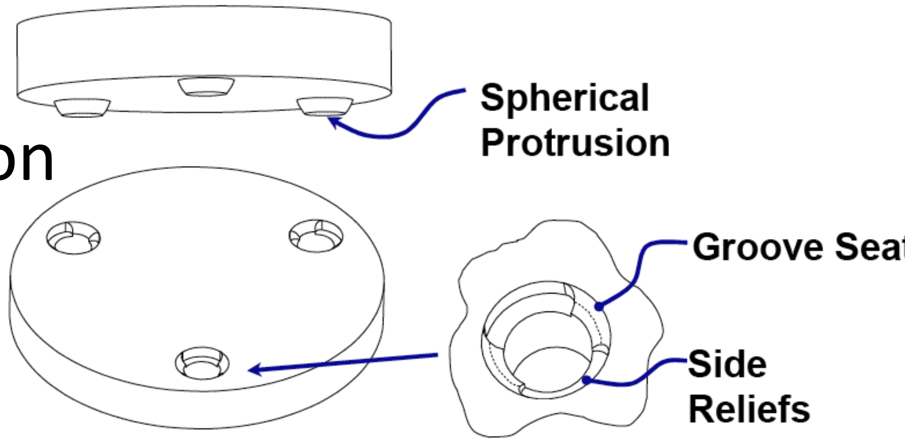


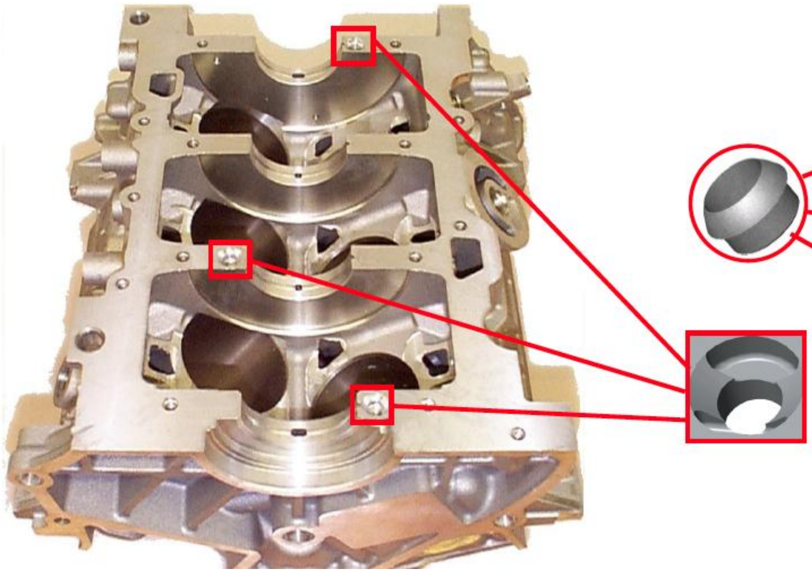
- What is a QKC & why is it important
  - Attain Sub-Micron Repeatability
  - Use Less Restrictive Tolerances
  - Have More Flexibility in Assigning

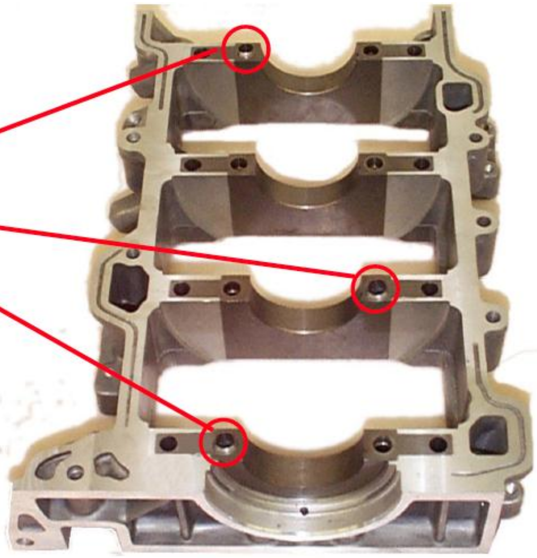
  Precision Tolerances
- Impact
  - Better Precision At Lower Cost
  - Extension of Practical HVM Precision
  - Eliminate Precision Pinned Joints (0.5 -10 microns)
  - Reduce Number of Parts

QKCs Physical Components

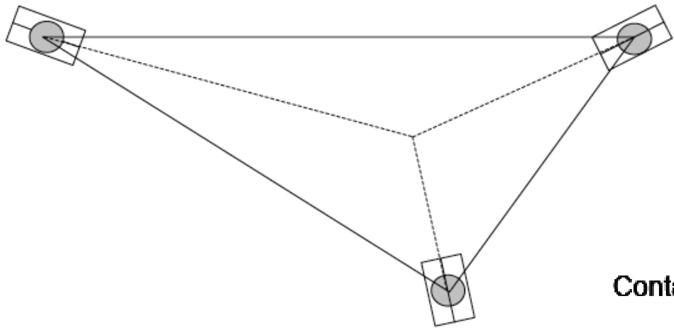
- Arc Contact
- Sub-micron Precision
- Stiffness Increase
- Sealing Contact



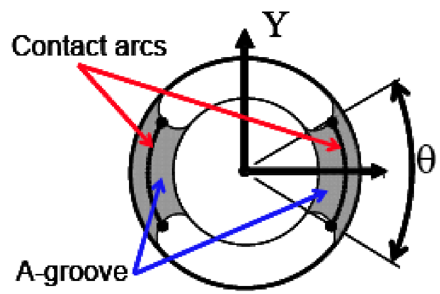


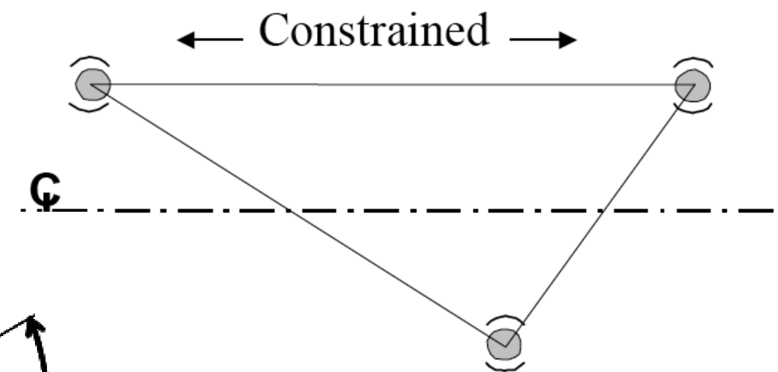


QKC Design



Kinematic Coupling



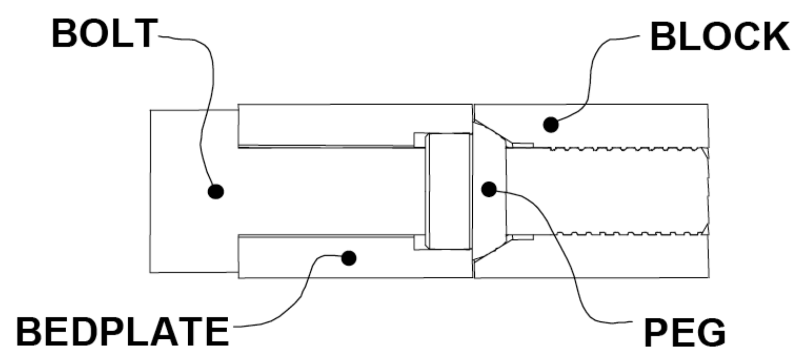


Aligned QKC

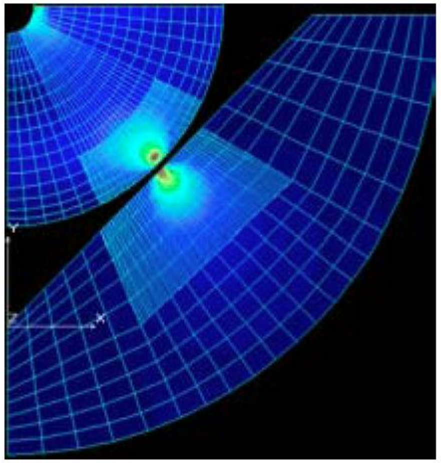
GROOVE MANUFACTURING

CAST FORM TOOL FINISHED

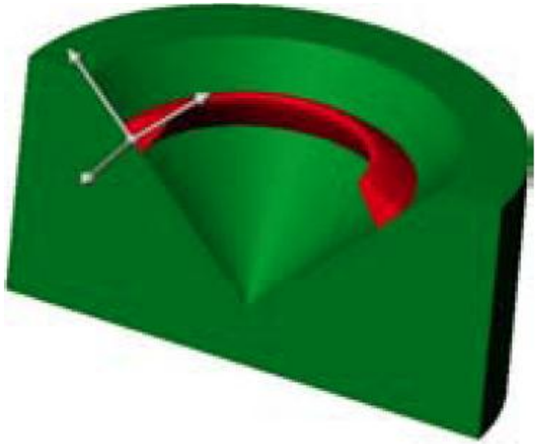
ASSEMBLED JOINT

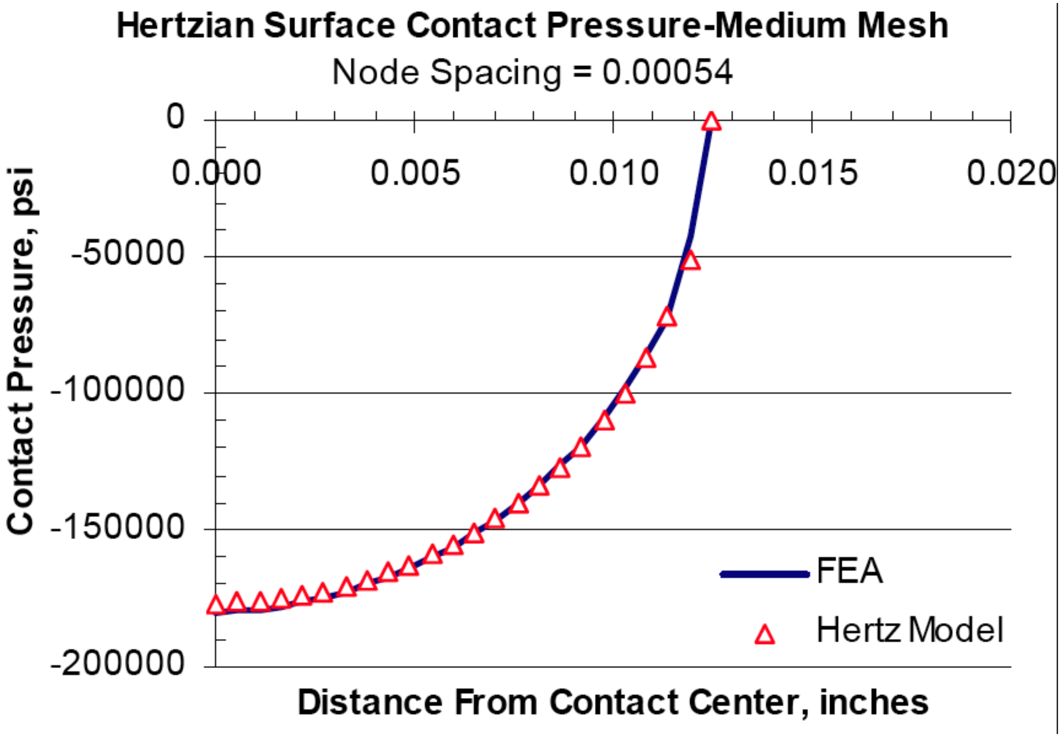


QKC Contact Mechanics



- Assume Hertzian Line Contact Profile
- Specify Profile in Rotating Coord. System
- Integrate Profile to get forces





Engine Assembly Comparison

- Manufacturing

Pinned Joint

Op. #10	→	Op. #30	→	Op. #50	→	Op. #100
• Mill Joint Face • Drill/Bore **16 Holes** • Drill Bolt Holes		• Drill Bolt Holes		• Press in **8 Dowels** • Assemble • Load Bolts • Torque Bolts		• Semi-finish crank bores • Finish crank bores

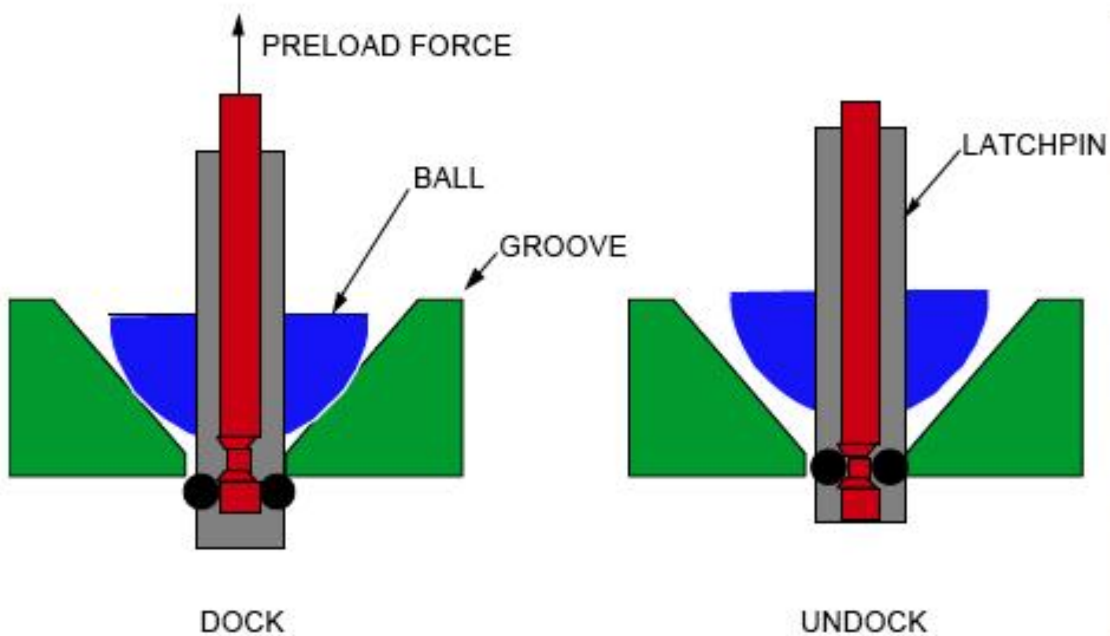
Using Quasi-KC Coupling

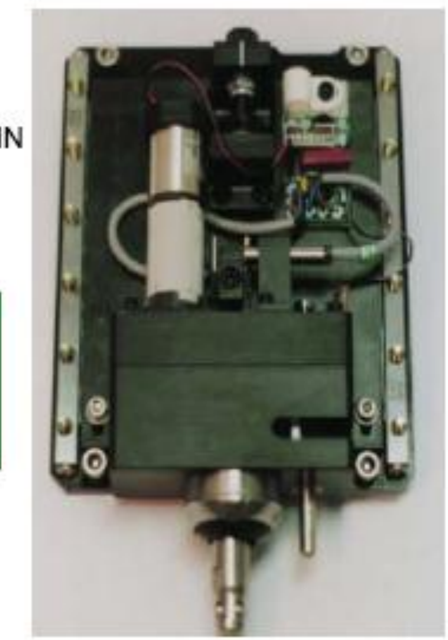
Op. #10	→	Op. #30	→	Op. #50	→	Op. #100
• Mill Joint Face • Drill/Bore **3 Peg** Holes • Drill Bolt Holes & Form **3 Conical Grooves**		• Drill Bolt Holes		• Press **3 Pegs in BP** • Assemble • Load Bolts • Torque Bolts		• Semi-finish crank bores • Finish crank bores

ITEM	QKC	Pinned Joints
# Precision Pieces	3	8
# Precision Features	3	16
Feature Placement Tolerance	+/- 0.08mm	+/- 0.04mm
Average Centerline Repeatability	0.65 μm	4.85 μm
Normalized $/Engine	0.64	1

Servo-Controlled KC

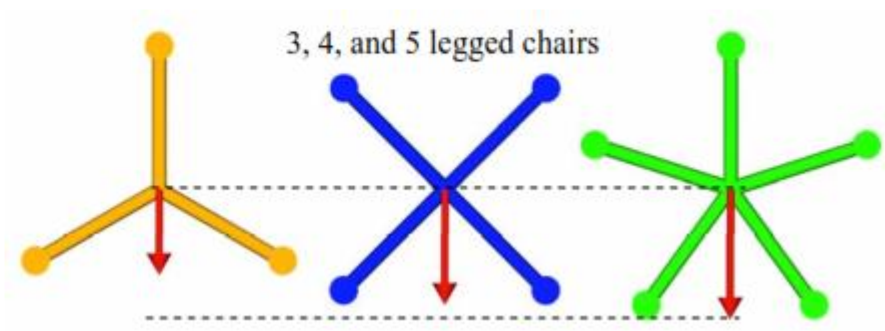
- Michael Chiu’s Doctoral Thesis
- Application: precision location and automatic leveling of precision electronic test equipment
- Teradyne has shipped over 500 systems

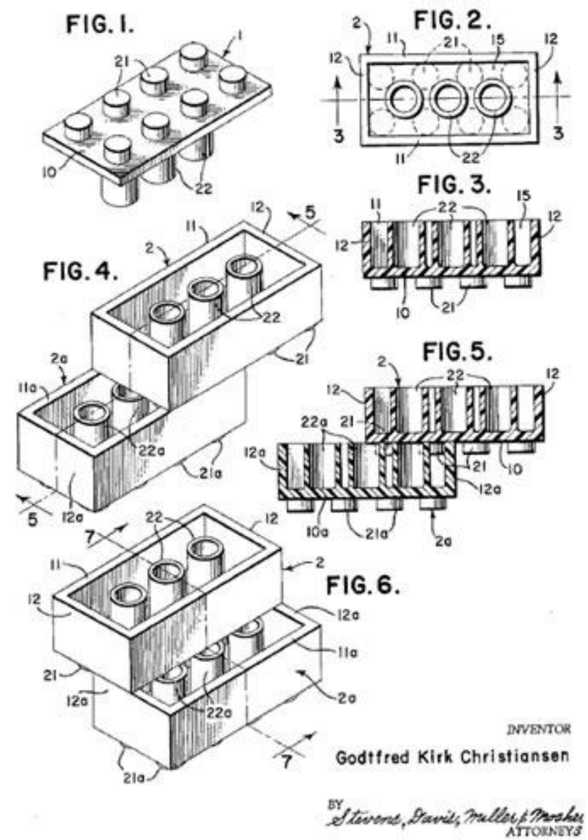




Elastic Averaging

- Multiple compliant contact points
- Members elastically deform
- High overall stiffness
- Application from toys,
  to office chairs to couplings



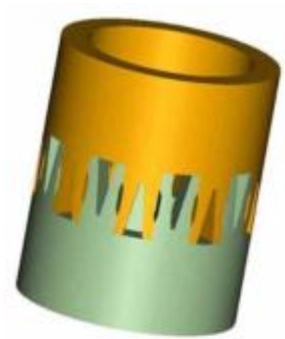


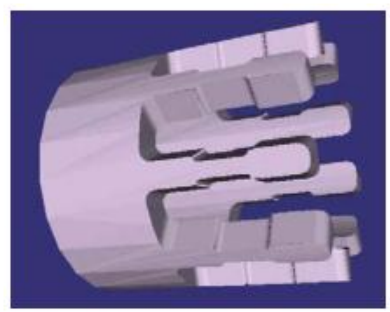
Anti Backlash Coupling

- Torsional couplings: spline, oldham, spyder



- Backlash causes noise, wear & failure
- Elastically averaged design based on multiple long, compliant fingers
- Low force, easy assembly, locked radially






Anti Backlash Coupling

- Load carried by multiple teeth
- Compliance provided by beam bending
- Radial flex accommodates finger variation
- Fingers self lock to prevent relative slip
- Chamfered ends for assembly
- No axial forces, good damping

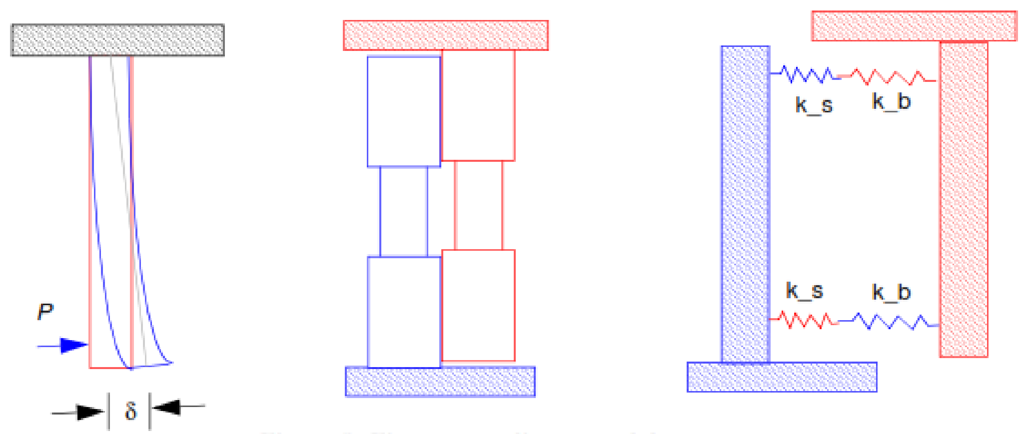


Figure 8: Finger compliance models

Thank you

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